APPLICATION
FOR
UNITED STATES LETTERS PATENT

Title: PERFORMANCE MONITORING OF OFFSHORE PETROLEUM RISERS USING OPTICAL STRAIN SENSORS

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PERFORMANCE MONITORING OF OFFSHORE PETROLEUM RISERS USING OPTICAL STRAIN SENSORS

Field of the Invention:

This application claims priority from United States Provisional Patent Application number 60/441,703, filed January 23, 2003 entitled "Fiber Optics Strain Measurement On Composite Tubulars", herein incorporated by reference in the entirety.

The present invention relates to a fiber optics system which provides the capable to measure in situ the strain and temperature in a long steel or composite tubular such as a riser used in offshore petroleum drilling and production operations and, more particularly, through engineering interpretation of the strain data to predict the fatigue life of the tubular and allow active controls to be used to mitigate damage from Vortex Induced Vibrations (VIV) imposed by ocean currents.

BACKGROUND OF THE INVENTION

Highly successful exploration and production of oil and gas in recent years from deepwater Gulf of Mexico (GOM) and other parts of the world have generated high interest in leasing, exploring and developing deepwater petroleum resources. Deepwater presents many new challenges with the design of risers, including the effects of Vortex Induced Vibrations (VIV), being an extremely important factor. Risers used in offshore drilling and oil and gas production provide a critical safety function as well as protection to the environment. These tubular structural elements must operate reliably in the harsh marine environment, sometimes for decades. As the water depth of exploration and production operations has increased, so has the challenge imposed on the design and reliability of risers. Corrosion or damage can occur, VIV can impose fatigue damage and high temperature can also become an issue. The capability to inspection and monitor riser performance has therefore become an important technology issue; particularly when the

inspection must be conducted in situ.

Although steel has been the material of choice for risers for decades, composite and titanium risers are increasingly gaining attention because of the weight and economic advantages they provide in deepwater. The composites and oil industry have supported research and development on composite risers for over fifteen years and although many believe the technology is ready for deployment, the expectation has not yet been fulfilled except in isolated trial deployments. Probably the most important factor limiting the acceptability of this needed service is the reluctance of regulatory agencies to approve introduction of this safety critical component without the accompaniment of reliable methods for inspection. The oil and composites industries likewise recognize the need for proven inspection methods to accompany into offshore service new safety critical applications such as composite risers.

One very important design constraint introduced for

deepwater risers is Vortex Induced Vibrations (VIV) and the effect it can have on the fatigue life of risers, particularly metal risers. Although metal components have established methods of inspection when there is ready access, in situ methods are not as well established or available. Composites exhibit different failure modes than metals and have different physical characteristics and specialized inspection methods such as ultrasonic, radiography, and acoustic emission have been used, however, they do not address the need to make deepwater in situ measurements. VIV is also a design concern for composite risers. The availability of in situ Non-Destructive Evaluation (NDE) monitoring techniques for high performance safety critical components such as risers is urgently needed in the petroleum industry to accelerate the acceptance of composites technology and to address safety and reliability concerns for both metal and composite components.

One very effective way of monitoring structural performance is to measure the strain response to load.

Strain can be compared to design predictions and monitoring the change in strain during service can be a very effective indicator of structural degradation due to overload, impact, environmental degradation or other factors. Fiber optics technology shows promise to provide a reliable in situ method to measure not only peak strain values but also the dynamic response imposed during VIV loading due to strong ocean currents such as Gulf of Mexico loop currents. Fiber optics technology can also be used to measure temperature which is also of interest to exploration and production operations. Fiber optics technology including Optical Time Domain Reflectrometry (OTDR) and Bragg defraction grating methods are ideally suited for in situ measurement of riser strain and temperature. Bragg gratings are particularly valuable for making local strain and temperature measurements while the Optical Time Domain Reflectrometry method is ideally suited for making global strain measurements such as the average strain over the length of a riser.

An OTDR measures spatial positions along an optical

fiber by launching brief pulses of light into one end of the fiber and then detecting the subsequent reflections at physical interfaces inserted along the length of the fiber. By measuring the transit time of the reflected pulses and by knowing the speed at which light travels in the optical fiber, a very accurate measure of the distance to each reflective interface can be attained. If a gauge section undergoes a strain, hence changes the interface's spatial position along the fiber, measurement of the change is length is a direct measurement of the average strain in the component. An OTDR with a picosecond pulsed light source can measure a change in length as small as 0.4-inch with an accuracy of about ±0.001 inch. A change in length of 0.4 in a 70-ft riser converts to a strain of 0.05% ±0.001%, which is sufficiently accurate to measure strains in the expected range of 0.07%. If needed, the accuracy can be increased in the riser application by making more than one traverse along the length of the pipe and thus provide a longer gage length. A single optical fiber can be used to measure strains at more than one location by imposing additional reflective surfaces along the length of the

optical fiber in combination with customized software algorithms to measure strain between each adjacent reflective interface. Measurement of the longitudinal strain in the composite tube provides valuable information about the state of the "fitness for service" of the composite tube when compared to design allowables and expected conditions.

Vortex-induced dynamic motion imposed by ocean currents typically have a period greater than 2 seconds and a wavelength involving several lengths of riser. Both the OTDR and Bragg Defraction Grating techniques can be used to measure the bending strains imposed by VIV on offshore marine risers, however, the OTDR method is considered to be the preferred method. With the OTDR method, the measured bending strains will have a value which is representative of the average radius of curvature. Although monitoring a single riser at a critical location may be sufficient, several risers at selected locations can also be monitored including the region adjacent to the ocean floor. By placing optical fibers sensors on diametrically opposite

sides of the tube, one can determine the strains due to bending which occur during the dynamic vibration imposed by the ocean currents, i.e., VIV. Since the direction of bending is not know, several diametrically opposed optical fiber sets must be introduced into the composite tube to be assured of obtaining the maximum bending effect.

Many methods have been developed to inspect the integrity of metal and composite components including ultrasonic, radiography, and acoustic emission. Each of these methods, however, does not address the need to inspect the component while performing the intended function in the marine environment. An in situ method is needed to monitor in real time the strains experienced by an offshore oil component such as a metal or composite riser. The fiber optics method of the current invention provides the capability to determine the state of fitness for service of these composite tubular components and provide the data needed to enhance safety and thus provide important operational safety quality assurance.

Visual inspection using a Remotely Operated Vehicle (ROV) is another method employed in offshore operations to inspect risers but a visual method is only superficial and does not provide detailed data such as strain or temperature needed to make precise engineering assessment of the structural integrity of the riser.

An Optical Time Domain Reflectrometry (OTDR) technique for measuring the strain in a mooring rope has been described in patent application No. 10/430.058 in which plastic optical fibers are used to make direct measurement of the large axial strains typically experienced by offshore platform mooring ropes (3% and higher). The strains in risers are significantly lower (less than 1%) and thus allow glass optical fibers to be used which exhibit much less attenuation (loss of light) than plastic optical fibers yet have a practical strain limitation well within the range of the riser application. The application of fiber optics to the riser application is significantly different from the rope application, however, the OTDR hardware required to make strain measurement is

generally applicable and is similar to that used in the telecommunications industry to measure the location of broken optical fibers.

The deficiency of the visual inspection method is that it reveals nothing about the strain or temperature in the riser or provide adequate information to assess Vortex Induced Vibration and most likely, for operational safety concerns, would not be available during the most critical load history of the riser such as during storms. In addition, it is difficult and expensive to reliably inspect risers in situ using ROV technology.

Traditional nondestructive inspection methods do not address the need to inspect and make measurements in situ in the marine environment.

It is therefore an object of the invention to describe an optical strain measurement system incorporating optical glass fibers or large strain plastic optical fibers integrally attached to the outside of a metal or composite

tube structure using a bonding agent such as epoxy and protected from the environment including sea water and service damage by the bonding agent and an additional layer of polymer or rubber-like material.

It is another object of the invention to provide a strain measurement system for assessing the structural integrity of laminated composite tubular structure or the metal to composite end connections based on strain measured using the methods described above.

It is another object of the invention to measure axial strains using the Optical Time Domain Reflectrometry (OTDR) fiber optics method by placing optical fibers along the axis of the metal or composite tubular starting at one end and traversing to the other end and if needed, to provide greater strain resolution; to loop the optical fiber back and forth as many times as needed to amplify the displacement magnitude.

It is another object of the invention to provide a

method using the Optical Time Domain Reflectrometry (OTDR) fiber optics method to measure average strains in a metal or composite tubular structure including measurement of average circumferential strains as well as average axial strains over a long length of the composite tube including from end to end.

It is another object of the invention to use the Bragg Diffraction Grating fiber optics method to measure local strains in a composite tubular structure in any direction, either circumferential or axial or at any angle to the axis of the tube, determined by design or test to be critical.

It is another object of the invention to provide a structural integrity monitoring system to determine strain concentrations and local anomalies by measuring average strains, either circumferential or axial or at any angle to the axis of the tube; in the metal to composite end connection of composite tubulars including risers using the Optical Time Domain Reflectormetry (OTDR) optical fiber strain measurement method. The preferred method is to wrap

the optical fibers onto the outside of the composite structure and to attach the optical fiber to the composite material using a bonding agent such as epoxy and to protect the optical fiber by the bonding agent and with an additional outside protective layer of polymer or rubber-like material.

It is another object of the invention to provide a structural integrity monitoring system for the metal to composite end connection commonly used in composite tubular construction using the Bragg Diffraction Grating optical fiber strain measurement method described above to measure local strains in the composite to metal end connection, either circumferential or axial or at any angle to the axis of the tube to determine local strain concentrations and local anomalies. The preferred method is to wrap the optical fibers onto the outside of the composite structure and to attach the optical fiber to the composite material using a bonding agent such as epoxy and to protect the optical fiber by the bonding agent and with an additional outside protective layer of polymer or rubber-like material.

It is another object of the invention to provide a technique utilizing Optical Time Domain Reflectormetry (OTDR) and axially oriented optical fibers to measure the dynamic response of composite tubulars subjected to cyclic vibration such as induced in a composite riser subjected to ocean currents, i.e., Vortex Induced Vibrations (VIV).

It is another object of the invention to provide a method for determining the magnitude of large bending strains induced by Vortex Induced Vibrations (VIV).

It is another object of the invention to provide a fiber optics method to measure the large axial and bending strains typically imposed on composite components such as spoolable composite pipe using plastic optical fiber composed of polymeric materials including polymethyl methacrylate and perfluorocarbon, which have strain capabilities exceeding 5-percent with relatively low attenuation.

It is another object of the invention to provide the design architecture for a coupling box to be attached to each end of the tube into which optical fibers are centrally located and protected. The optical fiber leads going into the coupling box are protected against bending and damage by the bonding agent and by the outer protective layer. The optical fiber leads are isolated against strain in the transition region by inserting them in a protective tube and by using a low modulus resin to attach them to the tube.

It is another object of the invention to provide a fiber optics coupling connector which bridges between individual joints of tubing. Such connector carries the optical fiber signal from the current joint as well as from tubing joints located at more remote distances from the data acquisition system and eventually to the surface.

It is therefore another object of the invention to provide a fiber optics method using Bragg Diffraction

Grating to provide in situ measurements of the temperature of a tubular in the marine environment including metal and composite risers used in offshore drilling and production operations.

It is therefore an object of the invention to provide a means to incorporate multiple plastic optical fiber strain sensors within a single riser joint.

It is therefore an object of the invention to provide a capability through multiplexing of the Optical Time Domain Reflectormetry (OTDR) and Bragg Diffraction instrumentation to allow numerous optical fibers or multiple reflections within the same fiber to be monitored using a single instrument.

SUMMARY OF THE INVENTION

In accordance with the present invention, there is provided a method for in situ measurement of the strain and

temperature of metal and composite tubulars located in the marine environment using optical fiber techniques including Optical Time Domain Reflectrometry (OTDR) or Bragg Diffraction Gratings. The method provides the capability to make axial, circumferential and off-axis strain measurements on the body of the riser and critical strain measurements in the metal to composite joint region typically used in composite risers. Through engineering analysis of the optical strain measurements, the method provides the capability to determine the bending strain and frequency of Vortex Induced Vibrations (VIV) imposed by marine ocean currents. The optical fibers of either glass or polymeric composition are located on the outside of either metal or composite risers following fabrication and bonded directly to the outer surface of the riser structural body and subsequently encapsulated in an outer protective cover. Bragg gratings are particularly valuable for making local strain and temperature measurements while the Optical Time Domain Reflectrometry method is ideally suited for making global strain measurements such as the average strain over the entire length of a riser and for

VIV monitoring. Multiplexing of the light signal allows monitoring of several plastic optical fibers and multiple segments within a fiber using a single light time-of-flight instrument. Strain measurements are transmitted to the surface either by a continuous optical fiber light path or by telemetry of a digitized signal.

BRIEF DESCRIPTION OF THE DRAWINGS

A complete understanding of the present invention may be obtained by reference to the accompanying drawings, when considered in conjunction with the subsequent, detailed description, in which:

Figure 1 is a side view of an of a metal or composite tubular indicating the positioning of fiber optics apparatus required to make strain and temperature measurements.; and

Figure 2 is a cross-sectional view of a the metal or composite tubular illustrated in Figure 1 illustrating the positioning of fiber optics apparatus relative to the metal or composite tubular structure..

For purposes of clarity and brevity, like elements and components will bear the same designations and numbering throughout the FIGURES.

DESCRIPTION OF THE PREFERRED EMBODIMENT

For purposes of brevity, the same elements and components will bear the same designation throughout the figures.

Now referring to Figure 1, which is a side view of a Metal or Composite Tube 10 indicating the positioning of fiber optics apparatus required to provide strain and temperature measurements. Axial Optical Fiber in Body of Tube 12 are positioned along the axis of the Metal or

Composite Tube 10 and the glass or plastic optical fibers are etched to provide capabilities consistent with either Optical Time Domain Reflectrometry or Bragg Diffraction Grating measurements. The Optical Time Domain Reflectometry optical fiber has a reflective interface at the end of the fiber making possible a gage length of the entire length of the Metal or Composite Tube 10. The Bragg Diffraction Grating is a localized grating on the order of 1-inch in length and thus provides measurements of local strain. Circumferential Optical Fiber 14 are so located to provide strain data about the circumferential or off-axis directions relative to the axial orientation of the tube. As with axially oriented optical fiber, strain measurements can be made using either Optical Time Domain Reflectrometry or Bragg Diffraction Grating techniques and optical fiber etchings.

Further refer to Figure 2, which provides a cross-sectional view of the composite tube and integrated optical fibers. The tube with a Metal or Laminated Composite Structure 30 usually has a Tube Interior Liner 32. Axial

Optical Fibers Looped End to End 36 allows an increase in the strain sensitivity of the Optical Time Domain Reflectrometry method by providing a longer gage length. A single end to end placement of optical fiber is adequate for long tubes such as risers used in offshore exploration and production.

The capability to provide bending and vibration information for loads imposed by Vortex Induced Vibrations (VIV) is provided by imposing Longitudinal Fiber Optics Circumferential Spacing 34 illustrated in Figure 2 with axial oriented optical fibers in a 45-degree spacing around the circumference. For bending strain measurements it is necessary to have strain information from opposite sides of the tube as provided by a 45-degree and other spacings.

The optical fibers are placed onto the outside of a Metal or Composite Tube 10 following the tube structural fabrication. The optical fibers are bonded using an adhesive such as epoxy directly to the tube and a Protective Outer Layer and Fluid Barrier 16 is laid over

the optical fiber to further protect it from impact and the marine environment. Similar protection is provided in the transition of Optical Fiber in Metal to Composite End Coupling 18 and into the Fiber Optics Connection Box 20 by overlaying the optical fibers with a polymeric or elastomeric material.

A Metal or Composite tube 10 is normally connected to adjacent tubes using a Threaded End Connection 22. In near proximity to the end connection is located a Fiber Optics Connection Box 20 which serves as the termination point for optical fibers and serves as the connection junction for transferring optical signals from one tube to the next tube and eventually to the surface and into a Optical Time Domain Reflectrometry or Bragg Diffraction Grating instrument which is used to process the data. An alternative way to transfer the strain and temperature data to the surface is to locate the Optical Time Domain Instrument or Bragg Diffraction Grating instrument in a control box attached to the tube, and digitize the data and send it to surface with electronic telemetry or hard wire.

The basic principals of the invention involve (1) attachment of optical fibers (glass or polymeric) to the outside body of the metal or laminated composite pipe structure, (2) protection of the optical fibers by the bonding agent and by a secondary outer protective layer typically required for other purposes including sealing a composite tube laminate against fluid intrusion, (3) application of the Optical Time Domain Reflectrometry (OTDR) and/or Bragg Diffraction Grating measurement technology to measure strain and temperature, (4) protection of the optical fiber leads from the end of the gage section into a central fiber optics connection box 20, and (5) method for transferring the data to the surface.

Glass or polymeric optical fibers are positioned at selected locations on the outside surface of the metal or composite tube 10 structure. Glass fibers have lower attenuation than polymeric fibers and are the preferred optical fiber of choice for measuring small strains (less

than approximately 1-percent) while plastic optical fibers such as polymethyl methacrylate or perfluorocarbon, which have strain capabilities exceeding 5-percent and relatively low attenuation for a polymeric optical fiber, are appropriate for large strain measurements. In general, the glass optical fiber capability is adequate for most high performance composite tubulars proposed for use in the oil industry such as risers. The utilization of fiber optics to measurement peak strains in spoolable composite pipe would require polymeric optical fibers since the strains imposed during spooling and service typically exceed 1-percent.

Integrating optical fibers into the composite laminate body is a difficult complication to impose during the manufacture of the composite structure (filament winding or other process), especially to maintain the integrity of the optical carrier leads. Fortunately, it is considered sufficient to determine the general state of structural integrity by measuring critical strains experienced by the exterior of the composite tube. The current technique is to attach the optical fibers on the exterior of the composite

structural laminate following manufacture in a separate operation. As discussed below, a variety of locations are proposed for the location of optical fibers including on the tube body and on the metal-to-composite end connection. The sequence is to finish the manufacture of the tube and end coupling and to carefully place the optical fibers onto the outside body of the tube and end coupling composite to metal interface using a bonding agent such as epoxy. In this process, the optical fiber end leads are also carefully extended into the fiber optics connection box 20. A low modulus resin or elastomer may be used to bond the fiber optics ends to the tube in the region of the end connection and if necessary the optical fiber can be inserted in a protective sleeve for protection and to eliminate strain imposed on the optical fiber in this transition region. Once the fibers are so located and bonded in place, an additional protection layer may be placed over this assembly. Such a protective outer layer is typically used for high performance tubular products such as deepwater composite risers in order to protect the composite structure during handling and to prevent the

ingress of sea water into the composite.

A discussion of the specific strain measurements of interest for primary tube structure applications are outlined below.

Tube Body Axial Strain Using OTDR

The axial strain in the body of the pipe is measured in a discrete local region using Bragg Diffraction Gratings while the average strain over a longer section of the tube is measured using the Optical Time Domain Reflectrometry (OTDR) strain measurement method. The OTDR method measures the time of flight for light reflected from reflective interfaces placed at selected locations along the length of the optical fiber and thus directly measures, through calibration, the change in the length between the two interfaces. These light reflection interfaces can be placed to provide strain measurements of short as well as long gage lengths. In one application the reflective interfaces would be placed at the each end of an optical fiber positioned from one end to the other end of the composite

tube and thus provide a strain measurement of the average strain over the entire length of the composite tube such as a riser. If greater accuracy is needed, the optical fiber could traverse back and forth from end to end of the composite tube as many times as needed to provide a longer gage length.

Measurement of the longitudinal strain in the composite tube provides valuable information about the state of the "fitness for service" of the composite tube when compared to design allowables and expected conditions. A further manifestation of the technology is for the measurement of strains imposed by Vortex Induced Vibration (VIV), a phenomenon of intense interest to oil company operators concerned about the safety of production and drilling risers. By placing optical fibers sensors on diametrically opposite sides of the tube, one can determine the strains due to bending which occur during the dynamic vibration imposed by the ocean currents, i.e., VIV. Since the direction of bending is not know, several diametrically opposed optical fiber sets must be introduced into the

composite tube to be assured of obtaining the maximum bending effect. Four or more sets of diametrically opposite optical fiber strain gage sets could be used to provide an axial optical fiber every 45-degrees or less around the circumference. Typically, the period of the imposed vibration is on the order of several seconds which is consistent with the capability to measure and record strains by the OTDR method.

With regard to VIV induced strain, the OTDR method using longitudinally-positioned, diametrically-opposite fiber optic sensor sets applies equally well to either metal or composite risers. The fiber optics technology application described herein would have an important role in enhancing the safety of offshore drilling and production operations.

Tube Body Axial Strain Using Bragg Diffraction Grating

As discussed above, optical fibers with Bragg Diffraction Gratings etched into an optical fiber can be used to measure local strain anomalies at selected

locations along the length of the tube. A single optical fiber can have several diffraction gratings etched on it. The data acquisition system can individually interrogate each grating and thus provide multiple local strain measurements using the same optical fiber.

Tube Body Circumferential Strain Using OTDR or Bragg Diffraction Grating

Measurement of the circumferential or off-axis strain can also be important for structural performance monitoring. The complete state of stress can be measured using a rosette of fiber optics (0/90/45) measuring strain in a common region of the tube. In this case the Bragg Diffraction Grating method would be the preferred technique. One of the advantages of measuring the circumferential strain is that it provides an indicator of local anomalies indicative of local damage or structural degradation. The optical fiber would be wound around the outside of the composite structure at an angle of approximately 65- to 90-degrees to the axis of the tube. A single gage length with reflective surfaces at each end of the tube is one

configuration productive for overall monitoring of the structural health of the structural tube. It may also be desirable to provide multiple reflective interfaces on a single optical fiber to capture information about discrete segments along the length of the tube. To obtain the necessary sensitivity, it will be necessary to make several revolutions between reflective interfaces. The optical fiber wind angle will determine the length of tube to be considered for each discrete gage length.

Metal to Composite Joint Strain Monitoring

Most high performance composite tubular components such as risers are connected together using a metal (steel or titanium) threaded coupling. The metal to composite transition coupling is often considered the most critical part of the composite tube. A trap-lock fitting involving winding composite fiber into circumferential recesses in the metal is one of several end couplings proposed for composite risers. The structural integrity monitoring method described herein is to monitor the strain in this region to detect if disbonds and damage propagation have

occurred. Optical fibers are wound around the outside of the composite structure in any direction or location desired as determined by design or experience to be the most critical area. Optical fibers wound in the circumferential direction are particularly effective using the OTDR measurement technique. The optical fibers are wound at an angle of 80- to 90-degrees relative to the axis of the tube. Several revolutions of the optical fiber are used between placement of reflective surfaces to allow a long gage length and high sensitivity of the strain measurement. Although this provides an average circumferential strain measurement, local strain anomalies will usually be sufficiently large to detect by the method. Bragg diffraction gratings can also be used to measure local strains in any direction desired.

End Connection Optical Fiber Integration

The optical fibers are integrated into a central connection box mounted on the side of the composite or metal tube. Optical fibers are protected in the region of the connection box by the outer protective layer applied to

the outside of the tube. In the region of transition from the point of measurement to the connection box, the optical fibers are inserted in a sleeve to prevent stains in the transition region from adding to the strains imposed in the gage section. Connector terminations developed by the telecommunications industry are used to collect large bundles of optical fibers. Optical signals from more remote tube sections are also introduced into the termination box. The signal from remote tubes are carried between connections using separate lines which can be located in a protective tube inside the tube outer protective layer or by a separate line attached to the tube.

Signal Transfer from Remote Sections of the Mooring Rope

Two approaches are available for transporting the optical signal to the surface. The first approach is to provide continuous optical fiber paths to the surface. This method requires that optical fiber connections be made between joints of the riser during installation. The

second method is to locate the OTDR instrumentation in close proximity to the riser and use hard wire or remote telemetry to transfer the digital date signal to the surface. As required, repeaters can be used to relay and amplify the signal.

Thus, in summary, it can be seen that what is provided in this invention is an in situ structural integrity monitoring system utilizing fiber optics technology to provide detailed strain and temperature information for metal and composite tubulars, particularly risers, used in deepwater petroleum drilling and production operations. Through engineering interpretation of the strain data, the method provides the capability to determine the magnitude of bending strains induced by Vortex Induced Vibrations (VIV) caused by strong ocean currents and the vibration frequency.

Since other modifications and changes varied to fit particular operating requirements and environments will be apparent to those skilled in the art, the invention is not considered limited to the example chosen for purposes of disclosure, and covers all changes and modifications which do not constitute departures from the true spirit and scope of this invention.

Having thus described the invention, what is desired to be protected by Letters Patent is presented in the subsequently appended claims.